Performance of optimized sound field control techniques in simulated and real acoustic environments

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Outline

• Introduction
• Sound field control techniques
• Motivation for numerical optimisation
• Optimisation procedure and cost function
• Experiments – anechoic simulations
• Experiments – automotive measurements
• Conclusions
Introduction

- Competing audio streams in a shared acoustic space
- Ideally this could be delivered over loudspeakers
• Competing audio streams in a shared acoustic space

$q = \begin{bmatrix} q_1 & q_2 & \cdots & q_j \end{bmatrix}^T$

$G_A = \begin{pmatrix} g_{A11} & g_{A12} & \cdots & g_{A1j} \\ g_{R_A} & g_{A22} & G_A^H & G_{A2j} \\ R_B & \vdots & G_B^H & G_B \\ g_{Ak1} & g_{Ak2} & \cdots & g_{Akj} \end{pmatrix}$

$p_A = \begin{bmatrix} p_{A1} & p_{A2} & \cdots & p_{Ak} \end{bmatrix}^T = G_A q$

$p_B = \begin{bmatrix} p_{B1} & p_{B2} & \cdots & p_{Bk} \end{bmatrix}^T = G_B q$
Sound Field Control Methods

Brightness Control (BC)
Choi and Kim (2002) ...
- Maximise acoustic potential energy in the target zone

Acoustic Energy Difference Maximisation (AEDM)
Shin et al. (2010)
- Maximise difference of acoustic potential energy between each zone

Acoustic Contrast Control (ACC)
Choi and Kim (2002), Elliot and Jones (2006) ...
- Maximise ratio of acoustic potential energy between each zone

Focus beam on target zone

Delay and sum beamforming

Maximise cancellation in terms of energy

Inverse methods

Specify exact desired sound field

Sound field synthesis
Sound Field Control Methods

Brightness Control (BC)
Choi and Kim (2002) ...

\[ \alpha_{\text{brightness}} = \frac{\varepsilon_A}{\varepsilon_{A \text{ max}}} = \frac{q^H R_A q}{\lambda_A q^H q} \]

Acoustic Energy Difference Maximisation (AEDM)
Shin et al. (2010)

\[ \alpha_{\text{diff}} = \frac{\varepsilon_A - a \varepsilon_B}{\eta} = \frac{q^H (R_A - a R_B) q}{q^H q} \]

Acoustic Contrast Control (ACC)
Choi and Kim (2002), Elliot and Jones (2006) ...

\[ \alpha_{\text{contrast}} = \frac{\varepsilon_A}{\varepsilon_B} = \frac{q^H R_A q}{q^H R_B q} \]

\( \lambda_A \)  Max. eigenvalue of \( R_A \)
\( \eta \)  Control effort
\( \varepsilon \)  Acoustic potential energy
Motivation for Optimisation

Where should we put the loudspeakers?!

- Classical configurations usually adopted for sound zone realisations
- **Line** e.g. Chang *et al.* (2009a, 2009b), Park *et al.* (2010)
- **Circle** e.g. Shin *et al.* (2010), Jacobsen *et al.* (2011)

Can we do better? What if these positions are unavailable?
Motivation for Optimisation

Where should we put the loudspeakers?!
Can we do better?
What if these positions are unavailable?

- Use numerical optimisation to select positions
- Improve separation performance:
  - Set up better conditioned problem
    Takeuchi and Nelson (2002), Bai et al. (2005)
  - Select the positions most appropriate for each zone
  - Vary selection over frequency
    Takeuchi and Nelson (2002)
Loudspeaker Selection Procedure

- Alternatives: exhaustive search, genetic algorithm...
- "Plus l – take away r" (sequential forward-backward search) Devijver and Kittler (1982)
- Computationally simple
- Sequential forward search

\[ Y(J_k + \xi_1) \geq Y(J_k + \xi_2) \geq \cdots \geq Y(J_k + \xi_{x-k}) \]

\[ J_{k+1} = J_k + \xi_1 \]
- Sequential backward search

\[ Y(J_k - \xi_1) \geq Y(J_k - \xi_2) \geq \cdots \geq Y(J_k - \xi_{x-k}) \]

\[ J_{k+1} = J_k - \xi_1 \]
- Parameters used: +2, -1
Cost Function

- Bai et al. (2005) proposed:
  \[ Y = Performance + W \cdot Robustness \]
  \[ Y_{\text{contrast}} = \text{SPL}_A - \max\{\text{SPL}_B, 0\} \]

- Atkins (2010) used matrix condition number as selection metric for WFS loudspeaker positions:
  \[ \arg\min \|W\|\|W^{-1}\| \]

- Proposed log reciprocal matrix number penalty:
  \[ Y_{\text{condition}} = 10 \log_{10} \left( \frac{1}{\|R_B\|_1\|R_B^{-1}\|_1} \right) \]

- Proposed cost function also includes term to constrain control effort:
  \[ Y_{\text{effort}} = 10 \log_{10} \left( \frac{q^H q}{q_{\text{ref}}^2} \right) \]

\[ Y = w_1 \cdot Y_{\text{contrast}} + w_2 \cdot Y_{\text{condition}} + w_3 \cdot Y_{\text{effort}} \]
Results – Anechoic Simulations

- Demonstrate value of cost function elements
- Choose array of 12 loudspeakers from 98 candidate positions on a circle (forward search)
- ‘Classical’ alternatives:

Circular array

Arc array
Results – Anechoic Simulations

• Demonstrate value of cost function elements
• Choose array of 12 loudspeakers from 98 candidate positions on a circle (forward search)

• ‘Classical’ alternatives:
  – Circle element spacing 77.5cm
  – Arc element spacing 9.6cm

• Simulation conditions:
  – Free-field anechoic room
  – Perfect monopole sources and microphones
  – Radius of circle – 1.5m
  – 2 circular zones – 30cm diameter
  – 7cm sound field sampling in zones
  – Spatially mismatched microphones for weight calculation/predictions
  – Simulations conducted in Matlab
Results – Anechoic Simulations (1kHz)

Circle

Contrast 56.6dB

Arc

Contrast 76.0dB

- Example based on acoustic contrast control

$w_1 = 1; w_2 = 0; w_3 = 0$
Results – Anechoic Simulations (1kHz)

Circle

Contrast 56.6dB

Contrast 76.0dB

Arc

Contrast 76.0dB

Contrast 76.0dB

- Example based on acoustic contrast control

CONTRAST PERFORMANCE:
- Selected sets perform better than circle
- Selected sets perform equivalently with arc

CONTROL EFFORT:
- Control effort constraint improves effort and ‘spill’ against all other cases
- General SPL level indicative of degeneration due to reflections

\[ w_1 = 1; w_2 = 0; w_3 = 0 \]

\[ w_1 = 1; w_2 = 0; w_3 = 1 \]
Results – Anechoic Simulations (1kHz)

Circle

$w_1 = 1; w_2 = 1; w_3 = 0$

Contrast 44.8dB

Contrast 76.0dB

$w_1 = 1; w_2 = 0; w_3 = 0$

$w_1 = 1; w_2 = 1; w_3 = 0$

Contrast 43.0dB

Contrast 49.5dB

- Example based on acoustic contrast control

MATRIX CONDITION:
- Optimal set produces equivalent contrast to previous cases

ROBUSTNESS:
- Random loudspeaker positioning error introduced
  $E \in (-1\text{mm}, 1\text{mm})$
- Produces best contrast case under error conditions
Results – Anechoic Simulations

• Anechoic simulations at 1kHz for alternative control methods

<table>
<thead>
<tr>
<th></th>
<th>Circle</th>
<th>Arc</th>
<th>Optimal $w_1=1, w_2=0, w_3=1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>16.2</td>
<td>18.1</td>
<td>26.7</td>
</tr>
<tr>
<td></td>
<td>-1.4</td>
<td>-3.6</td>
<td>-1.6</td>
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<tr>
<td>AEDM</td>
<td>53.3</td>
<td>71.8</td>
<td>76.0</td>
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<tr>
<td></td>
<td>-0.7</td>
<td>-3.0</td>
<td>-3.3</td>
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<tr>
<td>ACC</td>
<td>56.6</td>
<td>76.0</td>
<td>76.0</td>
</tr>
<tr>
<td></td>
<td>-0.4</td>
<td>-2.4</td>
<td>-5.9</td>
</tr>
</tbody>
</table>

• Contrast improved by selection procedure
• Optimise cost function weightings to improve effort for brightness control
• Effort ref. – single monopole closest to zone A producing same SPL
Motivation for Optimisation

Where should I put the loudspeakers?!

• **Practical problem in automotive environment**
  - Limitations on loudspeaker placement
  - Conventional arrays inappropriate
  - Errors exaggerated due to poor conditioning and measurement noise
  - Require a configuration for each zone

• **Comparison cases:**
  - All available loudspeakers
  - Line array of loudspeakers
Motivation for Optimisation

Where should I put the loudspeakers?!

- **Experimental setup:**
  - Backward search
  - TF measured using MLS
  - Candidate set: 38 midrange drivers
  - 40x40cm square zones, 7cm microphone spacing
  - Predictions generated by convolution in Matlab
Results – Automotive Simulations (1kHz)

- **All Loudspeakers**
  - Zone A: Contrast 18.5dB
  - Zone B: Contrast 13.4dB

- **Line Array**
  - Zone A: Contrast 12.2dB
  - Zone B: Contrast 13.1dB

- **Optimally Selected Set**
  - Zone A: Contrast 24.7dB
  - Zone B: Contrast 21.9dB

- Optimally selected set outperforms alternative configurations
Results – Automotive Simulations

Results at 1kHz for alternative control methods (Target Zone A)

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>Line</th>
<th>Optimal w₁=10, w₂=1, w₃=0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrast (dB)</td>
<td>8.6</td>
<td>7.6</td>
<td>14.3</td>
</tr>
<tr>
<td>Effort (dB)</td>
<td>-4.9</td>
<td>3.1</td>
<td>-3.3</td>
</tr>
<tr>
<td>AEDM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrast (dB)</td>
<td>19.0</td>
<td>8.9</td>
<td>24.2</td>
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<tr>
<td>Effort (dB)</td>
<td>4.8</td>
<td>19.1</td>
<td>6.2</td>
</tr>
<tr>
<td>ACC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrast (dB)</td>
<td>18.5</td>
<td>12.2</td>
<td>24.7</td>
</tr>
<tr>
<td>Effort (dB)</td>
<td>6.2</td>
<td>11.4</td>
<td>4.5</td>
</tr>
</tbody>
</table>

- Tentatively selected cost function weightings
- Contrast improved by selection procedure
- Cost function needs further development for effort performance
- Effort ref. – single driver closest to zone A producing same SPL
Summary

- Investigated issue of loudspeaker placement for creation of personal sound zones using BC, AEDM and ACC
- Numerical optimisation is necessary to choose ‘best’ set of loudspeakers for practical realisations of sound zones
- Cost function incorporated performance, robustness and effort measures
- Anechoic simulations demonstrated equivalent contrast and robustness improvement
- Control effort was improved in some cases
- Practical results in a real car show improvement in contrast against benchmark cases
References


